XMM-Newton OBSERVATIONS OF THE SPIRAL GALAXY M 74 (NGC 628)

ROBERTO SORIA[1] AND ALBERT K. H. KONG[2]
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ABSTRACT

The face-on spiral galaxy M 74 (NGC 628) was observed by *XMM-Newton* on 2002 February 2. In total, 21 sources are found in the inner 5′ from the nucleus (after rejection of a few sources associated to foreground stars). Hardness ratios suggest that about half of them belong to the galaxy. The higher-luminosity end of the luminosity function is fitted by a power-law of slope –0.8. This can be interpreted as evidence of ongoing star formation, in analogy with the distributions found in disks of other late-type galaxies. A comparison with previous *Chandra* observations reveals a new ultraluminous X-ray transient ($L_x \approx 1.5 \times 10^{39}$ erg s^{-1} in the 0.3–8 keV band) about 4′ North of the nucleus. We find another transient black-hole candidate ($L_x \approx 5 \times 10^{38}$ erg s^{-1}) about 5′ North-West of the nucleus. The UV and X-ray counterparts of SN 2002ap are also found in this *XMM-Newton* observation.

Subject headings: black hole physics — galaxies: individual: M 74 (NGC 628) — galaxies: spiral — X-rays: binaries — X-rays: galaxies

1. INTRODUCTION

M 74 (NGC 628) is an SA(s)c galaxy, seen almost face-on (inclination angle $\approx 5°$–$7°$, Shostak and van der Kruit 1984) at a distance of 9.7 Mpc (Tully 1988). It was observed by *XMM-Newton* on 2002 February 2, four days after the discovery of SN 2002ap (Nakano 2002) in the galaxy. In this Letter, we present the first results (including the luminosity function of X-ray sources, discovery of several luminous X-ray transients and the UV and X-ray counterparts of SN 2002ap) from this observation.

2. OBSERVATIONS AND DATA REDUCTIONS

The *XMM-Newton* instrument modes were full-frame, thin filter for the three EPIC cameras, and the UVW1 filter for the OM. The full time interval of the EPIC exposure is 34 ks. After rejecting intervals with a high background level, we considered a good time interval of 28 ks for our study. The exposure time for OM is 2.5 ks. The data were extracted and analyzed with the SAS version 5.2. We also compared our *XMM-Newton* observations with two *Chandra* observations taken on 2001 June 19 and 2001 October 19. The exposure time of both *Chandra* observations is about 47 ks. A full analysis of the *Chandra* data will be presented in a paper currently in preparation.

3. LUMINOSITY DISTRIBUTION OF THE X-RAY SOURCES

Twenty-one sources are detected by *XMM-Newton*/PN within 5′ from the galactic nucleus (not including a couple of sources coincident with foreground stars.) Eighteen of those sources were also found by *Chandra* in 2001 (one of them is in fact resolved into a close pair of sources by *Chandra*). However, three sources were not, and are likely to be transient. The completeness limit for the PN sources is $\sim 2 \times 10^{-3}$ cts s^{-1} in the 0.2–14 keV band. Assuming a power-law spectrum with $\Gamma = 1.7$ and column density $n_H = 10^{21}$ cm^{-2}, this corresponds to a flux of $\sim 7 \times 10^{-15}$ erg cm^{-2} s^{-1}, and an emitted luminosity of $\sim 1 \times 10^{38}$ erg s^{-1}.

Some of the 21 sources found inside the inner 5′ may be background AGN, seen through the disk of the galaxy, and therefore highly extincted. We can estimate the relative contribution of background sources by using the number counts from the *Chandra* Deep Field North survey (Brandt et al. 2001) in the 2–8 keV band (where absorption is not important). We obtain that about half of the sources should be attributed to the background, at the completeness limit for the PN in the 2–8 keV band (flux of $\sim 5 \times 10^{-15}$ erg cm^{-2} s^{-1}).

We can estimate the minimum total column density of hydrogen that would be between us and a background AGN, and use the observed hardness ratios to decide which sources are more likely to belong to the galaxy. By combining H I (Shostak & van der Kruit 1984) and CO (Adler & Liszt 1989) radio observations, and using a standard CO-to-H_2 conversion factor (Bloemen et al. 1986), we infer that the total column density N(H I+H_2) goes from $\sim 3.5 \times 10^{21}$ cm^{-2} in the inner 30″ to $\sim 1.5 \times 10^{21}$ cm^{-2} at a distance of 4′, and $\sim 1 \times 10^{21}$ cm^{-2} at 5′. To this, we need to add a foreground Galactic H I column density $n_{H,Gal} \approx 0.5 \times 10^{21}$ cm^{-2} (Dickey & Lockman 1990). Hence, we expect that background AGN would be seen through a total column density $n_H \gtrsim 1.5 \times 10^{21}$ cm^{-2}.

Defining as S and H the PN count rates in the (0.2–1.5) and (1.5–14) keV bands respectively, we obtain hardness ratios HR = (H–S)/(H+S) for the detected sources. For a source with a power-law spectrum with $\Gamma = 1.7$, typical of an AGN, HR = 0 if $n_H = 1.9 \times 10^{21}$ cm^{-2}, and HR = –0.19 if $n_H = 1.0 \times 10^{21}$ cm^{-2}. We have therefore taken HR < -0.2 as an empirical criterion to identify sources very likely to belong to M 74, while we cannot tell whether harder sources are background AGN or highly absorbed M 74 objects.

Nine of the 12 brightest sources detected with PN have HR < -0.2, hence we conclude that they are genuine M 74 objects. Figure 1 shows the cumulative luminosity function log[N(>S)]–log S for all the sources, and for the 9 sources with a most likely galactic origin. The latter curve can be fitted with a simple power law of index –0.8. This is similar to the slope at the high-luminosity end of the luminosity function for the disk population in spiral galaxies such as M 81 (Tennant et al. 2001) and M 101 (Pence et al. 2001). We shall present a detailed discussion of the position, luminosity and hardness ratios of all *XMM-Newton* and *Chandra* sources in a forthcoming paper.

[1] Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Surrey, RH5 6NT, UK; rs1@mssl.ucl.ac.uk
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; akong@cfa.harvard.edu

4. SPECTRAL ANALYSIS OF INDIVIDUAL SOURCES

4.1. *A new Ultraluminous X-ray Transient*

The brightest source in the field of M 74, located at R.A. = $1^h\,36^m\,36^s.5$, Dec. = $15^\circ\,50'\,36''$ (J2000), is one of the three sources found by *XMM-Newton* but clearly below the detection limit ($\sim 10^{37}$ erg s^{-1}) of both *Chandra* observations. Energy spectra were extracted with the SAS task XMMSELECT and were analyzed with XSPEC version 11. We extracted data in PN from a circle of $30''$ centered on the source, and the background from an annulus with inner and outer radii of $45''$ and $75''$, respectively. For the MOS images, in which the source is near the chip boundary, we took two source-free regions ($60''$ radius each) near the source for the background. In order to allow χ^2 statistics to be used, all the spectra were binned such that the signal-to-noise ratio ≥ 4. We fitted the PN and MOS2 data simultaneously with several spectral models: power-law, black-body + power-law, thermal bremsstrahlung, disk blackbody, and the bmc comptonisation model, in all cases with interstellar absorption.

All models provide statistically acceptable fits to the data ($\chi^2 \lesssim 1$; Table 1). The single power-law model yields a somewhat high column density compared to the values (foreground Galactic plus intrinsic) expected at that galactic radius. In contrast, the disk blackbody model (Mitsuda et al. 1984), and the bmc model (Shrader & Titarchuk 1999) provide lower values of $n_{\rm H}$. Physically, the comptonization model represents a two-component spectrum, with a soft blackbody component from the accretion disk and a power-law tail at higher energies, produced by inverse-Compton scattering of the soft photons by high-energy electrons. The best-fitting bmc model is shown in Figure 2. Neither the bmc nor the blackbody + power-law fits can simultaneously constrain the column density and the temperature of the thermal component.

The X-ray luminosity of XMMU J013636.5+155036 is significantly above the Eddington limit for a $1.4M_\odot$ accreting neutron star ($\sim 2\times10^{38}$ erg s^{-1}). With the disk-blackbody model, the best-fitting parameters of $T_{in} = 1.3\pm0.2$ keV and $R_{in}\sqrt{\cos\theta} = 47^{+12}_{-11}$ km imply a 0.3–8 keV luminosity of about 1.4×10^{39} erg s^{-1}. The bmc model yields an emitted luminosity of 1.6×10^{39} erg s^{-1}.

4.2. *Other individual sources*

There is another bright X-ray transient at R.A. = $1^h\,36^m\,27^s.2$, Dec. = $15^\circ\,50'\,05''$ (J2000); it was not seen in either *Chandra* observations. Its spectrum can be well fitted with a simple power law with photon index of $1.7^{+0.6}_{-0.3}$, $n_{\rm H} = (1.9^{+1.3}_{-1.4})\times10^{21}$ cm^{-2}. The emitted 0.3–8 keV luminosity is about 5.2×10^{38} erg s^{-1}, which makes it a likely stellar-mass black hole (BH) candidate. Compared to Galactic X-ray transients during outbursts, the spectrum of this source is relatively hard, although the errors are too large to constrain the exact spectral shape. Hard X-ray transients are seen in other external galaxies such as M 31 (Trudolyubov, Borozdin, & Priedhorsky 2001; Kong et al. 2002) and M 81 (Ghosh et al. 2001).

A third possible transient, detected by *XMM-Newton* but not *Chandra*, is located at R.A. = $1^h\,36^m\,38^s.6$, Dec. = $15^\circ\,44'\,20''$ (J2000). With a PN count rate of $(1.7\pm0.05)\times10^{-3}$ cts s^{-1}, it is too faint for a spectral analysis. Assuming a power-law spectrum with $\Gamma = 1.7$, and column density $n_{\rm H} = 10^{21}$ cm^{-2}, its emitted luminosity is $\sim 8\times10^{37}$ erg s^{-1} in the 0.2–14 keV band. The nucleus of the galaxy is detected at a count rate of $(4.8\pm0.7)\times10^{-3}$ cts s^{-1}, which corresponds to a luminosity of $\sim 2\times10^{38}$ erg s^{-1} for the assumed spectral model.

Finally, the X-ray counterpart of SN 2002ap (Nakano 2002) is detected at a count rate of $(3.1\pm0.5)\times10^{-3}$ cts s^{-1}. (Count rates in the two bands: S = $(1.4\pm0.4)\times10^{-3}$ cts s^{-1}; H = $(2.0\pm0.5)\times10^{-3}$ cts s^{-1}). This corresponds to $L\approx 6\times10^{37}$ erg s^{-1}for thermal plasma emission at 0.5 keV, or $L\approx10^{38}$ erg s^{-1}for a thermal Bremsstrahlung at 2 keV. SN 2002ap is also clearly detected in the OM image (Figure 3). We measure a flux $f_{\lambda,{\rm UV}}\approx 7.7\times10^{-15}$ erg cm^{-2} s^{-1}Å^{-1}, at an effective wavelength of 291 nm, on MJD 52307.0153.

5. DISCUSSION

5.1. *X-ray luminosity function in galactic disks*

The cumulative luminosity function is a useful tool for studying populations of X-ray sources in galaxies. In some cases, it is a broken power-law, with a change in slope at luminosities varying between a few times 10^{37} and a few times 10^{38} erg s^{-1}. In other galactic environments, the slope is constant from the detection limit to the high-luminosity end. A relation between the star-formation history of a galaxy and the evolution of its X-ray luminosity function has been proposed by Wu (2001) and Kilgard et al. (2002). Assuming that the brightest X-ray sources also have the shortest life, the luminosity function develops a break at its bright end in the absence of ongoing star formation. This is usually the case in elliptical galaxies and in the bulges of spiral galaxies. The break evolves towards lower luminosities over time. An unbroken power-law shape can instead be sustained if the X-ray source population is continuously replenished by star formation processes, as is the case for example in the arms of spiral galaxies.

In this scenario, the unbroken power-law luminosity function observed in the late-type spiral M 74 is consistent with recent or ongoing star formation. Previous optical and UV studies (Cornett et al. 1994) have shown evidence for recent star formation in this galaxy, probably not uniformly across the disk. They have also shown that the optical/UV colors of M 74 are intermediate between those of M 33 (bluest, with more recent star formation) and of the M 81 bulge (with an older stellar population). A comparison between the luminosity functions of these three galaxies is left to a work in preparation.

5.2. *The nature of XMMU J013636.5+155036*

Objects with an X-ray luminosity $\sim 10^{39}$–10^{41} erg s^{-1} are often called ultraluminous X-ray sources (ULXs; e.g., Makishima et al. 2000; Kaaret et al. 2001; Matsumoto et al. 2001). The X-ray spectra of ULXs are well described by a disk blackbody model (see however Strickland et al. 2001) with $T_{in}\sim 1.0$–1.8 keV and $R_{in}\sqrt{\cos\theta}\sim 20$–200 km. Our disk-blackbody fit to the *XMM-Newton* spectrum of XMMU J013636.5+155036 is in good agreement with these values. Although some ULXs are highly variable on timescales of months or years (e.g., Kubota et al. 2001; Strickland et al. 2001; La Parola et al. 2001), they always remain at a high luminosity state ($\gtrsim 10^{39}$ erg s^{-1}). However, XMMU J013636.5+155036 is undetectable in the two deep *Chandra* observations few months before our *XMM-Newton* observations, suggesting that the source was then below 10^{37} erg s^{-1}. The only transient ULX found so far is CXOU J112015.8+133514 in NGC 3628 (Strickland et al. 2001), while XMMU J013636.5+155036 is the only example of an off-center ($\sim 4'$ or ~ 10 kpc from the galactic center) transient ULX.

The nature of ULXs is still a subject of debate. One common interpretation is that they are powered by accretion onto an intermediate-mass BH (10^2–$10^4 M_\odot$; Colbert & Mushotzky 1999). If the fitted spectral parameter $T_{\rm in}$ (color temperature of the disk-blackbody) corresponds to the effective temperature $T_{\rm eff}$ at the inner boundary of a Shakura-Sunyaev disk, values of $T_{\rm in} \gtrsim 1$ keV would be inconsistent with an intermediate-mass Schwarzschild BH. Either a rapidly-spinning BH (Makishima et al. 2000) or non-standard disk models (e.g., a "slim disk"; Watarai, Mizuno, & Mineshige 2001) would be required instead. However, it is more generally $T_{\rm in} = f T_{\rm eff}$, where the "hardening factor" $f \approx 2.6$ in some Galactic microquasars (Ebisawa et al. 2001; Titarchuk & Shrader 2002). Therefore, observed values $T_{\rm in} \approx 1$ keV do not rule out an intermediate-mass, non-rotating BH. An alternative scenario for persistent ULXs is based on anisotropic emission from more common intermediate- or high-mass X-ray binaries. Emission beamed towards us can produce the high X-ray fluxes observed in those systems (King et al. 2001) without the need for an intermediate-mass BH. For a transient system such as XMMU J013636.5+155036, further observations will tell us whether the brightening is due to a short-lived phase of super-Eddington accretion, or to a state transition like those observed in some Galactic microquasars (GRO J1655–40 and GRS 1915+105), which share similar spectral properties (e.g., Makishima et al. 2000).

We tried to ascertain whether the ULX can be associated with a supernova remnant (SNR) or a photoionized H II region, as found in some cases (Wang 2002). From archival Hα images taken by the 1.0 m telescope at Mount Laguna Observatory (Marcum et al. 2001), XMMU J013636.5+155036 is $\sim 5''$ North-West of an extended H II region, and a point-like object is within the X-ray error circle (see Figure 4). The point-like source appears more or less the same in both continuum-subtracted Hα images taken in 1991 and 1995. Optical spectroscopy of the extended H II region yields a ratio [S II]/Hα ≈ 0.18 (van Zee et al. 1998), significantly lower than the typical value (> 0.4) measured in SNR (e.g., Blair, Kirshner, & Chevalier 1981). Therefore, the extended Hα feature near XMMU J013636.5+155036 is likely a photoionized H II region associated with star formation.

We inspected the UV image taken with OM, simultaneously with the X-ray images. There is no obvious object within the X-ray error circle, to a limiting specific flux of $\sim 2 \times 10^{-17}$ erg cm^{-2} s^{-1} Å^{-1}, at an effective wavelength of 291 nm. As a comparison, the specific flux from a single B0 V star in M 74 would be ~ 10 times fainter at the same effective wavelength. If the point-like source in the Hα image at the position of XMMU J013636.5+155036 corresponds to an OB star cluster, the lack of UV detection may be due to high extinction, typical of a very young star-forming cluster (Marcum et al. 2001). The larger H II region South-East of the transient is instead well visible in the OM image (Figure 3).

The association with a young stellar population suggests that XMMU J013636.5+155036 is related to a high-mass X-ray binary. In addition, its strong variability ($> 100\times$) indicates that it is an accreting compact object rather than a SNR. Further observations at different wavelengths will be necessary to shed light on the nature and timing properties of the source.

6. CONCLUSIONS

We have studied the spiral galaxy M 74 with *XMM-Newton*. The luminosity function above $\sim 10^{38}$ erg s^{-1} is well fitted by a single power law of slope -0.8, similar to the values found for the source population in the disks of other spiral galaxies. We interpret it as evidence of ongoing star formation in the disk. The brightest source, located $\sim 4'$ from the nucleus, is a transient, undetected by *Chandra* a few months earlier. It has a luminosity $L_{\rm x} \approx 1.5 \times 10^{39}$ erg s^{-1}in the 0.3–8 keV band, and spectral features similar to those observed in ULXs in other galaxies. The source appears to be associated with a photoionized H II region. Another bright transient BH ($L_{\rm x} \sim 5 \times 10^{38}$ erg s^{-1}) is found at $\sim 5'$ from the nucleus. The nuclear source itself is weaker ($L_{\rm x} \approx 2 \times 10^{38}$ erg s^{-1}). We have also measured the luminosity of the X-ray and UV counterparts of SN 2002ap, 4 days after its optical discovery.

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TABLE 1
BEST-FITTING SPECTRAL PARAMETERS FOR XMMU J013636.5+155036

Model	n_H (10^{21} cm^{-2})	Γ	kT (keV)	$R_{in}\sqrt{\cos\theta}$ (km)	χ^2_ν/dof	Flux[a]
power-law	$2.4^{+0.4}_{-0.5}$	$2.0^{+0.2}_{-0.1}$			0.85/56	1.95
bremsstrahlung	$1.4^{+0.4}_{-0.3}$		$4.6^{+1.4}_{-1.0}$		0.91/56	1.53
disk blackbody	$0.4^{+0.3}_{-0.4}$		$1.3^{+0.2b}_{-0.2}$	47^{+12}_{-11}	1.14/56	1.26
bmc	$1.3^{+1.4}_{-0.3}$	$1.9^{+0.2}_{-0.4}$	$0.23^{+0.09}_{-0.23}$		0.86/54	1.49
bb+power-law	$2.3^{+1.9}_{-0.6}$	$1.9^{+0.3}_{-0.3}$	$0.22^{+1.53}_{-0.22}$		0.86/54	1.89

Note. — All quoted uncertainties are 90% confidence.

[a]Unabsorbed flux in 0.3–8 keV (10^{-13} ergs cm^{-2} s^{-1}).

[b]Color temperature $T_{\rm in}$.

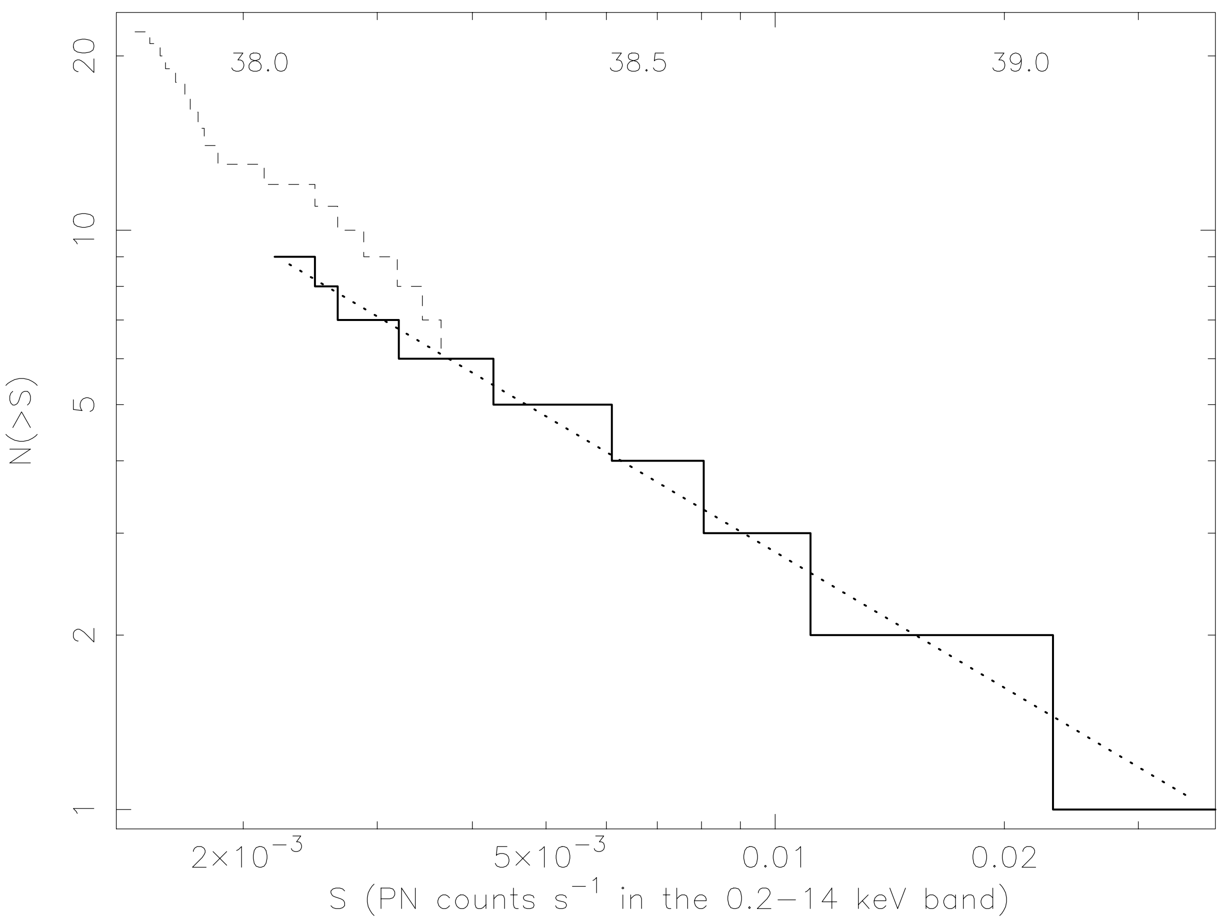

FIG. 1.— The log [N(>S)]–log S curve of the brightest sources in M 74 is well fitted with a power law of index –0.8 (dotted line). The thick solid line includes only relatively unabsorbed sources (HR < –0.2), likely to belong to the galaxy. The dashed line includes all the 21 sources found by *XMM-Newton* within a 5′ radius. At fainter fluxes, most of the sources may be background AGN. For the conversion between *XMM-Newton*/PN counts and unabsorbed luminosity, we have assumed power-law spectra with $\Gamma = 1.7$, $n_{\rm H} = 10^{21}$ cm^{-2}, $d = 9.7$ Mpc.

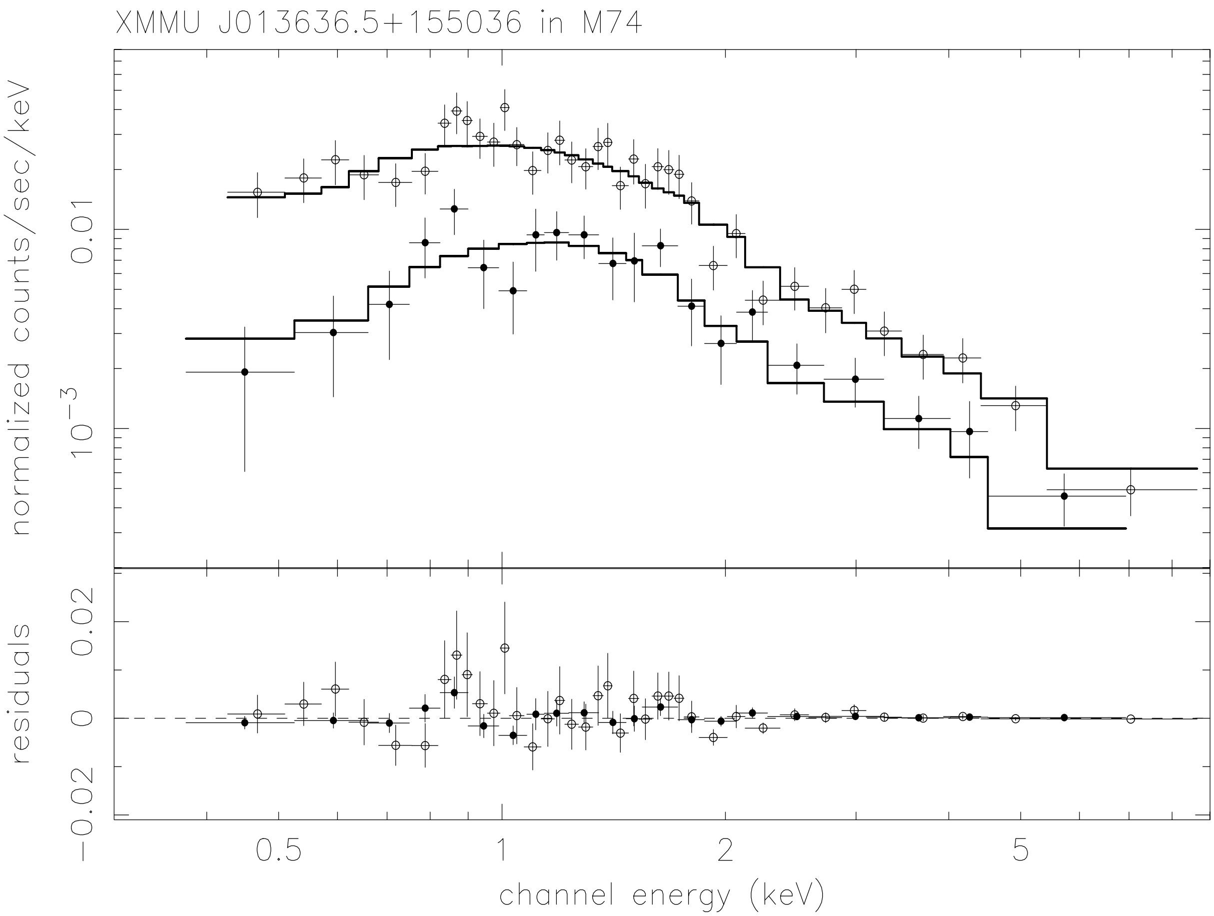

FIG. 2.— *XMM-Newton*/PN (open circles) and MOS2 (filled circles) spectra of the ultraluminous X-ray transient XMMU J013636.5+155036, fitted with an absorbed bmc model (parameters in Table 1).

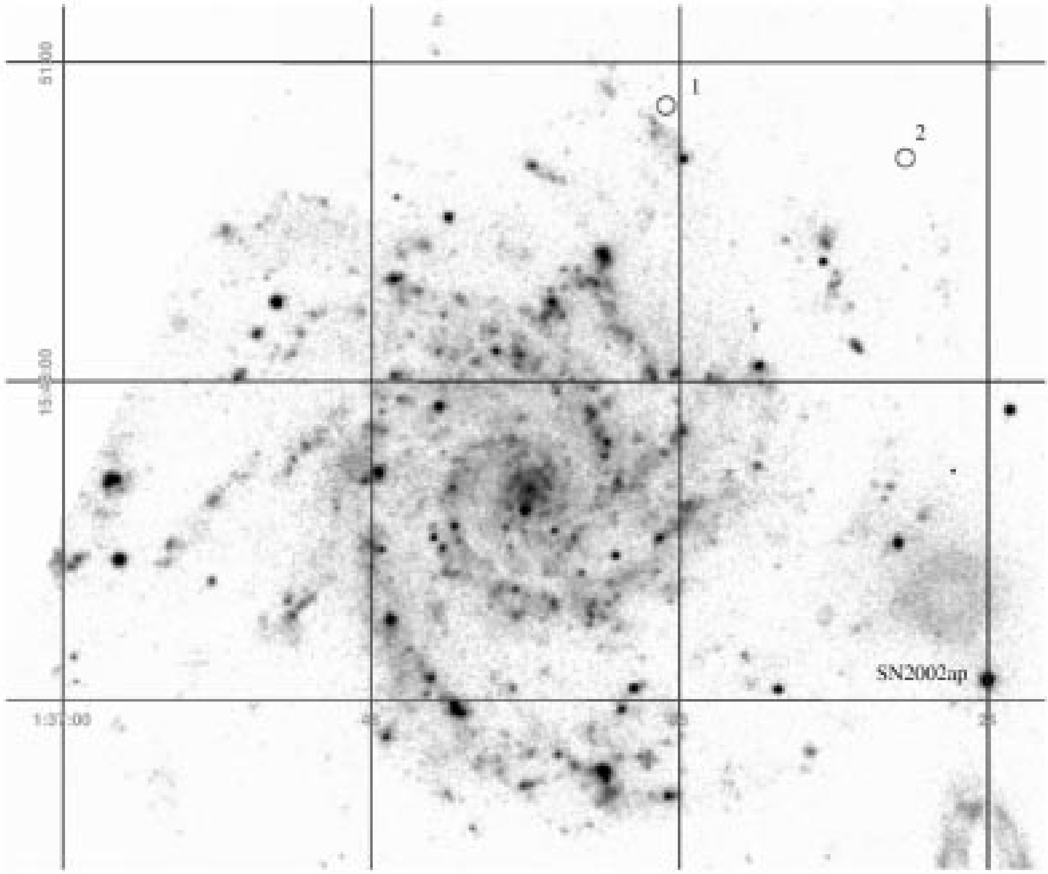

FIG. 3.— SN 2002ap is clearly visible at the bottom right of the *XMM-Newton*/OM image, taken in the UVW1 filter (North is up, East is left). The position of the two brightest X-ray transients is indicated with the circles (radius = 5′′) near the top of the image: 1 = XMMU J013636.5+155036, 2 = XMMU J013638.6+154420. (The two extended ring features at the bottom right of the image are due to reflected light onto the OM detector).

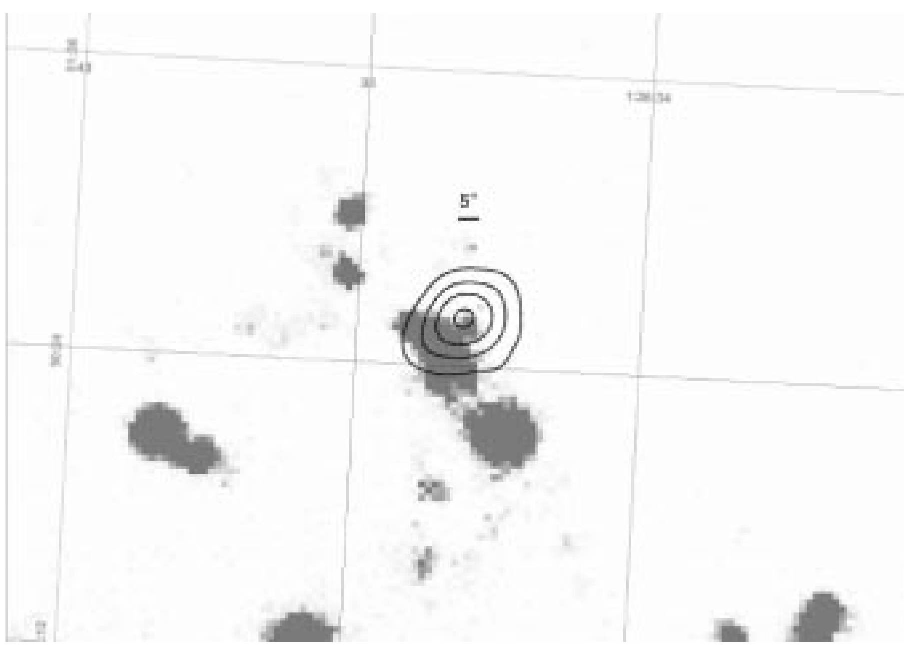

FIG. 4.— *XMM-Newton* PN intensity contours (at 10%, 25%, 50% and 90% of the maximum pixel value) of XMMU J013636.5+155036 overlaid on an archival continuum-subtracted Hα image taken from the Mount Laguna Observatory 1.0-m telescope in 1995.